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CALIBRATION OF THE PYLON AB-5/AEP SYSTEM, A CONTINUOUS RADON DAUGHTER WORKING LEVEL MONITOR

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by

J. Bigu*

ABSTRACT

A technical evaluation and calibration of several radon daughter continuous Working Level monitors have been conducted in a large Radon/Thoron Test Facility (RTTF). The monitors have been developed and manufactured by Pylon Electronics Development (Ottawa, Canada). Tests were conducted under the following environmental conditions: low relative humidity and low aerosol concentration, high relative humidity and low aerosol concentration, and high relative humidity and high aerosol concentration. The radon gas concentration in the RTTF was maintained within ±10% over extended periods of time. Radon daughter Working Levels were either maintained within ±10% for some tests, or were changed substantially during an 8 hour period to study the response of the instrument under rapid Working Level fluctuation. Under low relative humidity and low aerosol concentration, the monitors underestimated the Working Level by up to 18%. Under high relative humidity and high aerosol concentration, the sensitivity of the instruments decreased substantially after about 72 hours of continuous operation. Some suggestions and recommendations are made to improve the performance of the monitors.

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ÉTALONNAGE DU SYSTÈME PYLON AB-5/AEP, MONITEUR EN CONTINU DE L'UNITÉ ALPHA (WORKING LEVEL) DES PRODUITS DE FILIATION DU RADON

J. Bigu*

RÉSUMÉ

L'évaluation et l'étalonnage techniques de plusieurs moniteurs en continu de l'unité alpha (Working Level) des produits de filiation du radon ont été effectués dans une large enceinte servant à l'expérimentation sur le radon (thoron). Les moniteurs ont été mis au point et manufacturés par Pylon Electronics Development (Ottawa, Canada). Les essais ont été menés dans les conditions environnementales suivantes: humidité relative basse et faible concentration d'aérosols, humidité relative élevée et faible concentration d'aérosols et enfin, humidité relative élevée et concentration élevée d'aérosols. La concentration de radon dans l'enceinte a été maintenue dans l'intervalle de $\pm$ 10 % sur des périodes de temps prolongées. L'unité alpha (Working Level) des produits de filiation du radon a été maintenue dans l'intervalle de $\pm$ 10 % pour certains essais, ou a été modifiée considérablement au cours d'une période de 8 heures afin d'étudier la réaction de l'instrument soumis à des fluctuations rapides de l'unité alpha (Working Level). Au cours des essais à humidité relative basse et à faible concentration d'aérosols, les moniteurs ont sous estimé l'unité alpha (Working Level) jusqu'à 18 %. Lors des essais à humidité relative élevée et à concentration élevée d'aérosols, la sensibilité des instruments a diminué considérablement après environ 72 heures de fonctionnement en continu. Le présent rapport contient aussi quelques suggestions et recommandations visant à améliorer le rendement des moniteurs.

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INTRODUCTION

Radiation environments pose potential hazards to human health, hence, the need for adequate monitoring of radiation levels. Radiation monitoring is also important for engineering purposes such as the maintenance of reliable air quality control in working areas.

Monitoring of the short-lived decay products of radon, i.e., radon daughters, in uranium mines for dose exposure purposes is mandatory in Canada and other countries. Radon daughter levels in dwellings of residential areas must be on average below 0.02 WL, where WL stands for Working Level.

Radon and radon daughter levels can be measured by means of a variety of instruments of the passive and active type, using techniques which range from grab-sampling to time-integrating and continuous monitoring, employing a variety of radioactivity counting methods.

The degree of accuracy with which the radiation level can be measured depends on the type of instrument, and technique and method used. If the technique and method used are standardized, i.e., if kept the same, the ultimate accuracy of radioactivity measurements depends directly on the type of instrument used. Hence, calibration of radiation instrumentation in well-known, i.e., standard, radioactivity atmospheres is very important. Calibration of radon and radon daughter instrumentation is commonly carried out in special installations known as radon chambers.

This report presents data on a technical evaluation and calibration of a commercially available radon daughter Working Level monitor developed by Pylon Electronics Development (Ottawa, Canada). The monitor consists of a multipurpose scaler Model AB-5 and a sampling head Model AEP-25 or AEP-47. For simplicity, the monitor will be referred to hereafter as the AB-5/AEP system. In its usual way of operation this system has been designed to operate on a continuous basis.

The evaluation of the instrument was conducted in a large Radon/Thoron

Test Facility (RTTF). The calibration of the monitor was requested by the Atomic Energy of Canada Limited (AECL) for a monitoring and remedial action program in some Elliot Lake dwellings.

DESCRIPTION OF THE AB-5/AEP SYSTEM

The scaler Model AB-5 is a microprocessor-controlled instrument which consists of a photomultiplier tube, a scaler provided with digital read-out and a non-volatile memory, and a variable flow rate sampling pump that can operate between 0.1 and 4.0 L/min, according to the manufacturers specifications. The photomultiplier tube is located at the end of a re-entrant cavity where the AEP sampling head is located.

The scaler Model AB-5 was used in conjunction with a radon daughter sampling head Model AEP-47 or AEP-25 consisting of a ZnS(Ag) screen detector facing a filter holder where a Nuclepore filter 47 mm or 25 mm diameter was located, respectively. The sampling head is designed to fit snugly into the photomultiplier tube of the AB-5. Radon daughters are drawn through the filter by means of the variable flow rate sampling pump which is usually adjusted to operate at a flow rate of 1 L/min. The sampling head is of the 'true' open face type in that radon daughters are directly deposited on the outer face of the filter, i.e., the side opposite to the side facing the ZnS(Ag) screen detector. This mechanical configuration is possible in clean, i.e., non-dusty, atmospheres because the α-particle absorption on Nuclepore filters is quite low.

The AB-5/AEP monitor is designed to operate continuously, although it can also operate intermittently. The monitor is programmable, i.e., the sampling time and frequency of the counting periods can be chosen at will. Data can be stored in the memory unit and retrieved at a later time, or it can be printed out by means of an external printer. If the data do not need to be displayed in real

time, i.e., by the digital read-out and/or the printer, but they are to be retrieved at a later time, an interface unit Model CI-55 is required.

The monitor provides α-particle count accumulated during the pre-programmed sampling time. Conversion of α-particle count to radon daughter Working Level, WL(Rn), is done with the help of specially developed computer software which uses a theoretical conversion factor to convert α-particle count-rate, in counts per minute (cpm), into WL(Rn). Other factors involved in the calculation of WL(Rn) from cpm include the sampling head α-particle counting efficiency, the filter absorption characteristics, plate-out considerations in the sampling head, and the sampling pump flow rate.

Five AB-5 scalers were used, each operating in conjunction with a different AEP sampling head. The following AB-5/AEP sets were used: AB-5 #202 with AEP-25 #106; AB-5 #205 with AEP-47 #114; AB-5 #207 with AEP-47 #111; AB-5 #208 with AEP-47 #119; and AB-5 #209 with AEP-47 #108.

The operating characteristics (settings and other variables) for the AB-5/AEP system were as follows:

High voltage setting	:	2.0
Discriminator setting	:	4.0
Sampling flow-rate	:	1.0 L/min
Sampling time	:	60 min
Counting efficiency	:	0.121 (±5%)
Conversion factor K	:	17250 counts WL^{-1}

EXPERIMENTAL PROCEDURE

Testing and calibration of the monitors were conducted in a large (26 m^3) Radon/Thoron Test Facility (RTTF) (1). The monitors were tested under laboratory-controlled environmental conditions of temperature, relative humidity, and aerosol concentration.

Tests were conducted during March 1985, and during the period June-July,

1985. Tests conducted in March are not included here because of some instrument malfunction, some incorrect information given to the Elliot Lake Laboratory regarding instrument settings, uncertainty with regards to pump flow-rates, as recommended by the manufacturer, difficulties in maintaining a given flow-rate, and other problems.

The particular environmental conditions for each test are given in the section on experimental results. In broad terms, however, the range of some of the environmental conditions in the RTTF were as follows. Temperature varied between 22°C and 29°C with a maximum temperature variation during a 24 hour period of $\bar{<}4$°C. The average temperature during the test was about 25°C. The relative humidity varied between 32% and 86%. The maximum variation in relative humidity during a 24 hour period was <3%. Experiments were preferentially conducted at low relative humidities (30 to 45%) and at high relative humidities (76 to 86%).

Aerosol concentration was varied from less than 1.0×10^3 cm^{-3} to ~ 8.0×10^4 cm^{-3}. The aerosol concentration ranges of interest were: low ($\bar{<}1.0 \times 10^3$ cm^{-3}), intermediate (1.0×10^3 cm^{-3} - 3.0×10^3 cm^{-3}), and high (1.0×10^4 - 8.0×10^4 cm^{-3}).

Two major operating conditions were selected, namely: low aerosol concentration (~1.0×10^3 cm^{-3})/low relative humidity ($\bar{<}40$%), and high aerosol concentration ($\bar{>}6.0 \times 10^4$ cm^{-3})/high relative humidity (≈85%). An aqueous solution of NaCl (1 g/L) was used to produce the aerosol cloud. Aerosol were generated using an atomizer manufactured by TSI (Minneapolis, U.S.A.) Model 3076, in conjunction with its associated air supply system, column desiccator, and electrical charge neutralizer, also manufactured by TSI.

The two relative 'extreme' operating conditions used, indicated above, were used in order to study plate-out effects in the monitor sampling heads. Plate-out effects are known to occur preferentially at low aerosol concentrations, thereby leading to significant errors in the estimation of

WL(Rn). The case of low aerosol concentration is important in dwellings of non-smoking individuals, particularly during the winter period in cold countries such as Canada, where the low relative humidity compounds with the low aerosol concentration.

High relative humidity/high aerosol concentration conditions are important to measure the effect of filter 'loading' in radon daughter instruments of the active kind. Filter loading leads to a decrease in the detector/sampling head counting efficiency, and hence to an underestimation of WL(Rn). For instruments that use α-spectrometry principles, filter loading leads to a broadening of the spectrum and a shift of the photopeaks to lower energies. These effects are caused by α-particle absorption and self-absorption effects in the filter materials, partially induced by the deposition of aerosol and water vapour. The case of high aerosol concentration/high relative humidity is relevant to underground uranium mines where the above conditions prevail and can lead to substantial errors in the estimation of WL(Rn). Furthermore, the presence of high concentrations of corrosive aerosols and water vapour is known to affect the performance of the detectors and electronic circuitry of radiation instruments.

Experiments were conducted within a narrow range of radon gas concentrations, [^{222}Rn], i.e., 40-50 pCi/L. Radon daughter Working Levels ranged from 0.02 to 0.4, these changes being brought about by changing the aerosol concentration and relative humidity in the RTTF.

During some tests, the WL(Rn) was maintained constant within about ±10% for periods of 8 to 24 hours, depending on the nature of the test. In addition, rapid increases and decreases in the WL(Rn) were also introduced to study the response and performance of the radon daughter monitors to abrupt WL(Rn) changes.

Radon and radon daughter atmospheres were produced by injecting radon gas (^{222}Rn) into the RTTF by means of radon gas flow-through sources Model Rn-1025

manufactured by Pylon Electronic Development (Ottawa, Canada). Radon gas and aerosol were injected into the RTTF through injection ports located opposite to the air exhaust system.

Radon gas in the RTTF was continuously monitored by means of two radon gas monitoring systems, the Radon Gas Monitor Model RGM-2, manufactured by Eberline (U.S.A.), and an in-house developed radon gas monitoring system operating on similar principles to those of the RGM-2. The RGM-2 and the in-house developed system provided radon gas concentrations measurements every hour and every 20 min, respectively. In addition, radon gas concentrations were periodically measured by grab-sampling, using the scintillation cell method, and by the two-filter method (2,3).

Radon daughter concentrations were measured by grab-sampling using the Thomas-Tsivoglou method (4). Radon daughter Working Levels were also measured using the Thomas-Tsivoglou method, and the Kusnetz method (4,5). Radon daughter concentrations and WL(Rn) were measured every 40 min. A calibrated Working Level monitor, Model WLM-300, manufactured by EDA, was also used to record the WL(Rn) continuously, i.e., one measurement every hour.

Radon gas and radon daughter measurements were conducted at least at two different locations simultaneously in an area where radiation instruments to be calibrated were located. Results from different locations were taken and an average value was calculated in each case.

Air temperature, relative humidity and barometric pressure were measured using a meteorological package manufactured by alpha-NUCLEAR, (Toronto, Canada) consisting of a data logger, Model 601, in conjunction with air temperature, dew point and barometric pressure probes, Models 602, DS-001, and 604, respectively. Aerosol concentration was measured by drawing air samples continuously, in a recirculating mode, through two condensation nuclei counters, Model Rich 200, manufactured by Environment 1 (U.S.A.), and Model 3020, manufactured by

TSI (U.S.A.).

The WL monitors to be tested were placed in a large three-shelf metal mesh structure so designed as to produce minimum disturbance to the air flow in the RTTF. All monitors were placed on the same shelf. Care was taken to minimize mutual monitor interference, or disturbance of air patterns by the monitors.

The WL(Rn) measured by the AB-5/AEP monitors was compared with grab-sampling data as follows: The WL(Rn) from the AB-5/AEP monitors and by grab-sampling were plotted, versus time, on the same graph for direct comparison purposes, particularly to determine trending and the behaviour of the monitor under rapidly changing radiation levels.

Comparisons between the WL(Rn) for the AB-5/AEP monitors and grab-sampling were done during a period of time of 8 h/day, for several days, during which environmental conditions were changed. Daily average values for the WL(Rn) for the monitor and for grab-sampling were calculated, and the ratio of the two sets of values was computed for calibration purposes.

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental data obtained have been summarized in Tables 1 to 10 and in Figures 1 to 6. The tables show the following data. Radon daughter Working Level obtained with the AB-5, i.e., $\overline{WL}_{AB-5}$, and by grab-sampling in the RTTF by the Thomas-Tsivoglou method, i.e., $\overline{WL}_T$. Also shown are the ratio $\overline{WL}_{AB-5}/\overline{WL}_T$, the temperature (T), the relative humidity (RH), the aerosol concentration (N), and the radon daughter disequilibrium ratios (DR). The disequilibrium ratios are defined by the ratios $[^{214}Pb]/[^{218}Po]$ and $[^{214}Bi]/[^{218}Po]$. The third ratio shown as the first figure, is, by definition, unity, i.e., $[^{218}Po]/[^{218}Po]$. It should be noted that in the above ratios, the square brackets indicate activity

concentration. The horizontal bars on WL_{AB-5} and WL_T are used to denote the average value over an 8 hour period. The two values for T, RH, N, DR and WL shown in the tables indicate the minimum (top), and maximum (bottom) values measured during the 8 h/day period during which the calibration work was carried out.

Tables 1 to 4 show calibration data at low relative humidity and low aerosol concentrations. Under these conditions, the radon daughter concentrations, Working Level and disequilibrium ratios decrease considerably when compared with high relative humidity and high aerosol concentration conditions. This is so because at low aerosol concentrations, radon daughters readily plate-out on nearby surfaces.

Tables 1 to 4, and Figures 1 and 2, show the results obtained with the systems AB-5 (#207)/AEP-47 (#111), AB-5 (#208)/AEP-47 (#119), AB-5 (#209)/AEP-47 (#108), and AB-5 (#202)/AEP-25 (#106), under low relative humidity and low aerosol concentration conditions. The data show that under these conditions, the systems operate, on an average, reasonably well. Except for the fourth system, the other systems underestimate the Working Level by 18% to 3%. The fourth system, i.e., AB-5 (#202)/AEP-25 (#106) considerably underestimates the Working Level. However, in this case a 1 μm Nuclepore filter was used instead of the customary 0.8 μm Nuclepore filter. This difference in pore size may partly account for the large underestimation of the radiation level. The counting efficiency for this system, quoted by Pylon, was the same as that used for the AEP-47 sampling head. No appreciable deterioration in the performance of the above four systems was observed.

Tables 5 to 10, and Figures 3 to 6, show the results obtained with the systems: AB-5 (#202)/AEP-25 (#106), AB-5 (#209)/AEP-47 (#108), AB-5 (#205)/AEP-47 (#114), AB-5 (#208)/AEP-47 (#119), AB-5 (#207)/AEP-47 (#111), and AB-5

(#205)/AEP-47 (#114). The tests were mostly conducted at high relative humidity and high aerosol concentration. Furthermore, the Working Level on the RTTF was changed (via aerosol concentration) quite significantly during every day of the tests in order to investigate the response of the instruments under rapidly changing Working Level conditions.

Except for the system AB-5 (#205)/AEP-47 (#114), see Table 10, all of the other systems tested show an interesting feature, i.e., a progressive deterioration of the performance of the instrument with time. This behaviour is attributed to the accumulation of aerosol (NaCl) on the Nuclepore filter, effectively absorbing α-particles, and hence, significantly decreasing the α-particle counting efficiency of the sampling head/photomultiplier tube system.

The data also show that a quite appreciable deterioration in performance occurs after about 72 hours of sustained high aerosol concentrations. The role of the relative humidity in conjunction with the aerosol is not clear at this point. From these data one may conclude that if the instruments are to be used under the above environmental conditions, e.g., an underground uranium mine, care should be taken to change the filter frequently before adverse dust and aerosol effects occur.

The data obtained for the system AB-5 (#205)/AEP-47 (#114) are not conclusive because of a sudden increase in α-particle count beginning July 25 (13:00 h) for no apparent reason. The low ratio $\overline{WL}_{AB-5}/\overline{WL}_T$ obtained for the system AB-5(#202)/AEP-25(#106) (see Table 5) is not clear at this point. The usual 0.8 μm Nuclepore filter was used this time. Some pump-flow rate problems were observed, i.e., the flow-rate could not be maintained at 1 L/min. It is possible that the α-counting efficiency for this system suggested to the Elliot Lake Laboratory is in error.

REMARKS AND RECOMMENDATIONS

There are a number of serious concerns regarding the design and operation

of the AB-5 scaler and the AEP sampling head. Some considerations are briefly discussed below.

1. The instrument is not equipped with a servo-controlled sampling pump. Hence, the flow-rate is not maintained constant and air flow readjustment was required twice during an 8 h period. This is a very serious drawback, particularly when the instrument is in use overnight. The flow-rate was observed to drift toward lower values;
2. The lack of a servo-controlled sampling pump is further complicated by the fact that the instrument is not even provided with a flow-meter, as an integral part of the system. Hence, no continuous air flow monitoring is possible, unless an external flow-meter is installed externally by the user;
3. The high voltage and discriminator settings are located on the backside of the instrument. There is no potentiometer adjustment for fine tuning. Proper instrument setting is done by means of a screw-driver. It has been observed that the settings can slightly change during the operation of the instrument because of the vibration introduced by the pump;
4. The sampling head is susceptible to dust and aerosol deposition because the air enters the system through the side of the filter facing away from the detector. Hence, under dust or aerosol loading conditions, quite appreciable deterioration of the counting efficiency is observed due to α-particle absorption in the material accumulated on the filter;
5. At sufficiently high sampling flow-rate ($\geq$1 L/min and $\leq$4 L/min) the battery charger cannot maintain the charge on the AB-5 scaler for extended periods of time and the system stops operating and collecting data;
6. The AB-5/AEP system is not ruggedized, dust proof, or moisture proof, and hence unsuitable for field operations.

The AB-5/AEP system could be quite versatile and reliable should items 1 through 6 be taken into consideration. No doubt financial considerations play a

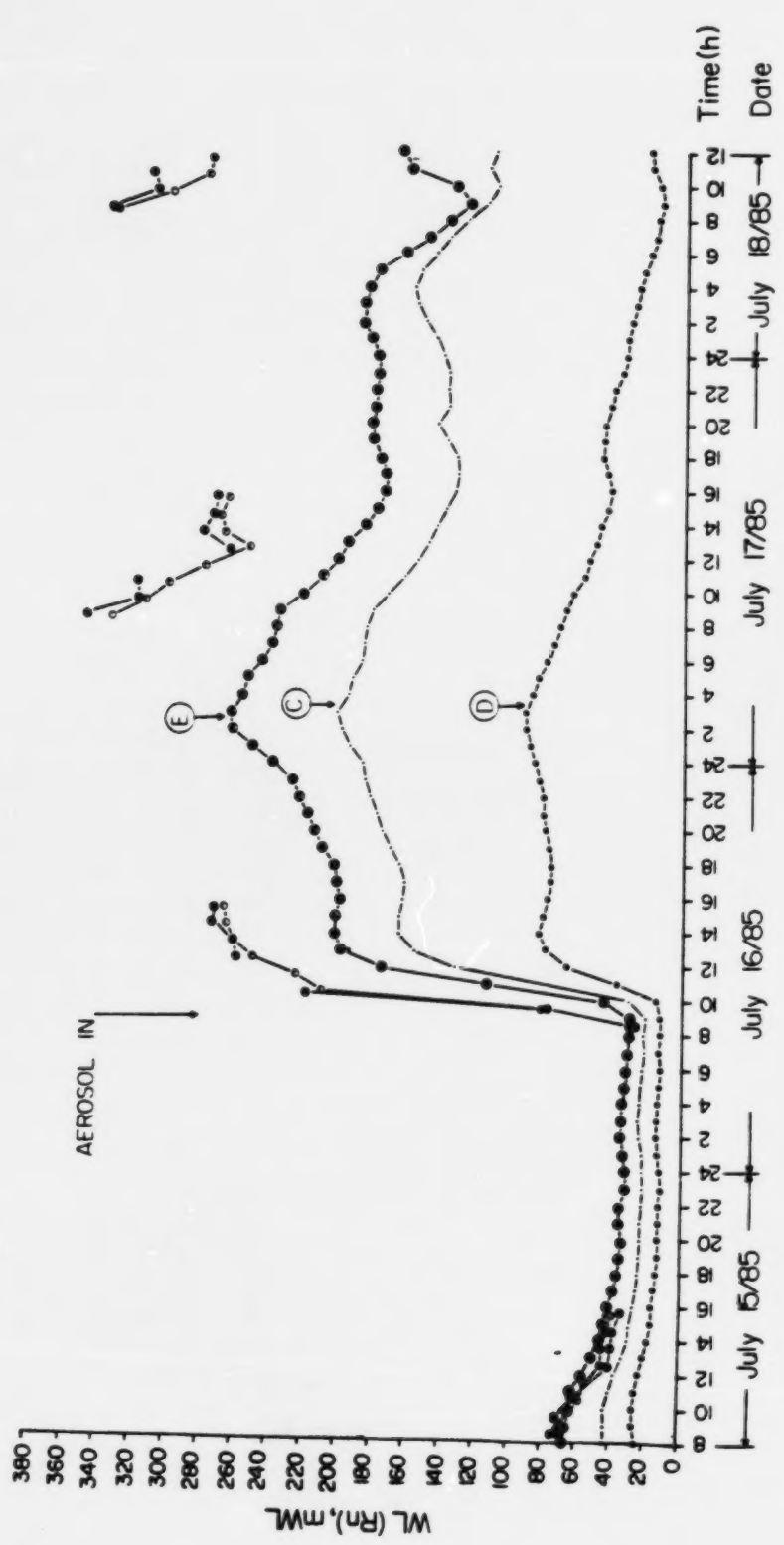

Fig. 3 - Working Level versus time for the systems AB-5 (#205)/AEP-47 (#114), curve E, AB-5 (#209)/AEP-47 (#108), curve C, and AB-5 (#202)/AEP-25 (#106), curve D. Encircled dots and solid dots represent grab-sampling data by the Thomas method and the Kusnetz method, respectively.

great role in the design of instrumentation, but the extra cost incurred in introducing the suggested modifications would be more than compensated by the extra flexibility and reliability that would be provided to the monitor.

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REFERENCES

1. Bigu, J., "A walk-in radon/thoron test facility"; Am. Ind. Hyg. Assoc. J., vol. 45, No. 8, pp 525-532; 1984.

2. Thomas, J.W. and LeClare, P.C., "A study of the two filter method for radon-222"; Health Phys., vol 18, pp 113-122, 1970.

3. Mayya, Y.S. and Kotrappa, P., "Modified double filter method for the measurement of radon or thoron in air"; Ann. Occup. Hyg., vol. 21, pp 169-176; 1978.

4. Thomas, J.W., "Measurement of radon daughters in air"; Health Phys., vol 23, pp 783-789; 1972.

5. Kusnetz, H.L., "Radon daughters in mine atmospheres"; Am. Ind. Hyg. Assoc. J., vol 17, p. 1; 1956. (See also Ind. Hyg. Quarterly, March 1956).

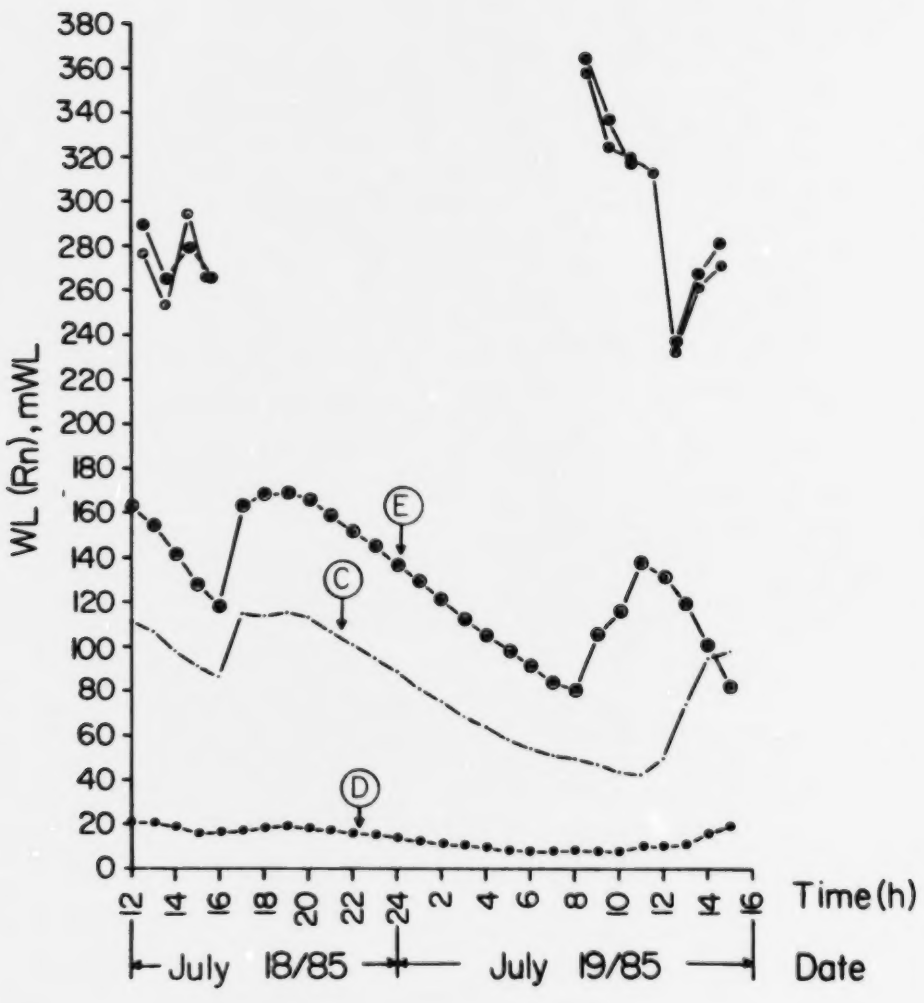

Fig. 4 - Working Level versus time for the systems AB-5 (#205)/AEP-47 (#114), curve E, AB-5 (#209)/AEP-47 (#108), curve C, and AB-5 (#202)/ AEP-25 (#106), curve D. Encircled dots and solid dots represent grab-sampling data by the Thomas method and the Kusnetz method, respectively.

Table 1 - Data pertaining to the calibration of the AB-5 #207 and AEP-47 #111 system in the RTTF.

Date	$\overline{WL}_{AB-5}$ mWL	$\overline{WL}_T$ mWL	$\overline{WL}_{AB-5}/\overline{WL}_T$	T °C	RH %	N cm^{-3}	DR	WL_T mWL	Remarks
June 19/85	25.3±1.8	31.8±1.9	0.79	24.4	36.5	$\sim 0.4 \times 10^3$	1:0.1:0.1	31	
				26.0	39.0		1:0.18:0.08	37	
June 20	28.0±2.9	33.5±2.4	0.83	25.0	36.4	0.42×10^3	1:0.12:0.1	32	
						0.65×10^3	1:0.21:0.14	39	
June 21	35.4±3.8	41.8±4.4	0.85	25.0	34.9	0.65×10^3	1:0.17:0.15	38	
						1.3×10^3	1:0.25:0.18	53	
		Ave:	0.82±0.03						

Table 2 - Data pertaining to the calibration of the AB-5 #208 and AEP-47 #119 system in the RTTF.

Date	$\overline{WL}_{AB-5}$ mWL	$\overline{WL}_T$ mWL	$\overline{WL}_{AB-5}/\overline{WL}_T$	T °C	RH %	N cm^{-3}	DR	WL_T mWL	Remarks
June 18/85	44.2±6.4	40.5±5.1	1.09	26.0	40.0	$\lesssim 1.0 \times 10^3$	1:0.15:0.05	39	
							1:0.28:0.26	50	
June 19	28.3±0.5	31.8±1.9	0.89	24.4	36.5	$\sim 0.4 \times 10^3$	1:0.1:0.1	31	
				26.0	39.0		1:0.18:0.08	37	
June 20	31.9±3.5	33.5±2.4	0.95	25.0	36.4	0.42×10^3	1:0.12:0.1	32	
						0.65×10^3	1:0.21:0.14	39	
June 21	39.5±4.4	41.8±4.4	0.94	25.0	34.9	0.65×10^3	1:0.17:0.15	38	
						1.34×10^3	1:0.25:0.18	53	
		Ave:	0.97±0.08						

Table 3 - Data pertaining to the calibration of the AB-5 #209 and AEP-47 #108 system in the RTTF.

Date	$\overline{WL}_{AB-5}$ mWL	$\overline{WL}_T$ mWL	$\overline{WL}_{AB-5}/\overline{WL}_T$	T °C	RH %	N cm^{-3}	DR	WL_T mWL	Remarks
June 24/85	17.8±0.6	21.5±1.1	0.83	24.6	33.1	$0.28x10^3$	1:0.08:0.07	21	
				26.0	33.4	$0.38x10^3$	1:0.14:0.04	25	
June 25	22.2±2.5	25.4±2.6	0.87	24.9	32.6	$0.65x10^3$	1:0.07:0.09	24	
				27.3	32.8	$1.25x10^3$	1:0.17:0.02	31	
June 26	24.5±0.9	31.6±2.4	0.77	26.0	31.0	$0.8x10^3$	1:0.1:0.08	29	
				30.1	31.5	$3.0x10^3$	1:0.21:0.1	36	
June 27	31.5±2.2	36.1±3.9	0.87	24.0	32.9	$0.65x10^3$	1:0.12:0.07	32	
				27.8	33.2	$1.5x10^3$	1:0.23:0.24	46	
June 28	35.1±3.4	43.6±5.4	0.80	24.8	35.5	$0.65x10^3$	1:0.19:0.15	37	
				28.9	36.8	$1.85x10^3$	1:0.28:0.08	56	
		Ave:	0.83±0.04						

Table 4 - Data pertaining to the calibration of the AB-5 #202 and AEP-25 #106 system* in the RTTF.

Date	$\overline{WL}_{AB-5}$ mWL	$\overline{WL}_T$ mWL	$\overline{WL}_{AB-5}/\overline{WL}_T$	T °C	RH %	N cm^{-3}	DR	WL_T mWL	Remarks
June 24/85	3.4±0.2	21.5±1.1	0.16	24.6	33.1	0.28×10^3	1:0.08:0.07	21	
				26.0	33.4	0.38×10^3	1:0.14:0.04	25	
June 25	4.5±0.5	25.4±2.6	0.18	24.9	32.6	0.65×10^3	1:0.07:0.09	24	
				27.3	32.8	1.25×10^3	1:0.17:0.02	31	
June 26	4.9±0.2	31.6±2.4	0.15	26.0	31.0	0.8×10^3	1:0.1:0.08	29	
				30.1	31.5	3.0×10^3	1:0.21:0.1	36	
June 27	6.1±0.4	36.1±3.9	0.17	24.0	32.9	0.65×10^3	1:0.12:0.07	32	
				27.8	33.2	1.5×10^3	1:0.23:0.24	46	
June 28	6.9±0.8	43.6±5.4	0.16	24.8	35.5	0.65×10^3	1:0.19:0.15	37	
				28.9	36.8	1.85×10^3	1:0.28:0.08	56	

* 1 μm (pore size) Nuclepore filter was used instead of 0.8 μm. The value used for the efficiency of the system was the same as that used for the AEP-47 sampling head with 0.8 μm Nuclepore filter. No efficiency value applicable to the present case was available at the time of the calibration. Hence, WL_{AB-5} needs to be corrected.

Table 5 - Data pertaining to the calibration of the AB-5 #202 and AEP-25 #106 system in the RTTF.

Date	$\overline{WL}_{AB-5}$ mWL	$\overline{WL}_T$ mWL	$\overline{WL}_{AB-5}/\overline{WL}_T$	T °C	RH %	N cm^{-3}	DR	WL_T mWL	Remarks
July 15/85	21.7±	52.0±	0.417	24.5	47.5	$0.55x10^3$	1:0.16:0.15	38	
				28.1	52.6	$2.8x10^3$	1:0.33:0.26	70	
July 16	77.8±	247.5±	0.314	24.8	59.7	$6.1x10^4$	1:0.55:0.33	226	Aerosol injected
				26.6	72.9	$7.0x10^4$	1:0.70:0.47	268	at 9:15+
July 17	58.7±	286.4±	0.205	24.3	77.0	$7.2x10^4$	1:0.57:0.39	254	
				27.5	80.0	$7.6x10^4$	1:0.77:0.64	334	
July 18	17.7±	285.0±	0.062	24.7	80.2	$7.5x10^4$	1:0.65:0.58	253	
				25.7	82.8	$8.0x10^4$	1:0.90:0.73	333	
July 19*	10.4±	297.1±	0.035	24.8	82.0	$2.7x10^4$	1:0.59:0.40	232	Some aerosol
				29.0	82.9	$8.0x10^4$	1:0.95:0.71	358	conc. instability

* Pump flow-rate could not be maintained at 1 L/min after 10:30. A value less than half the operating flow-rate was measured.

+ Before aerosol injection, the following values for N, DR and WL_T were measured: $0.45x10^3$ cm^{-3}, 1:0.14:0.04 and 31, respectively.

Table 6 - Data pertainining to the calibration of the AB-5 #209 and AEP-47 #108 system in the RTTF.

Date	$\overline{WL}_{AB-5}$ mWL	$\overline{WL}_T$ mWL	$\overline{WL}_{AB-5}/\overline{WL}_T$	T °C	RH %	N cm^{-3}	DR	WL_T mWL	Remarks
July 15/85	35.6±	52.0±	0.685	24.5	47.5	$0.55x10^3$	1:0.16:0.15	38	
				28.1	52.6	$2.8x10^3$	1:0.33:0.26	70	
July 16	156.2±	247.5±	0.631	24.8	59.7	$6.1x10^4$	1:0.55:0.33	226	Aerosol injected
				26.6	72.9	$7.0x10^4$	1:0.70:0.47	268	at 9:15+
July 17	161.0±	286.4±	0.562	24.3	77.0	$7.2x10^4$	1:0.57:0.39	254	
				27.5	80.0	$7.6x10^4$	1:0.77:0.64	334	
July 18	110.0±	285.0±	0.386	24.7	80.2	$7.5x10^4$	1:0.65:0.58	253	
				25.7	82.8	$8.0x10^4$	1:0.90:0.73	333	
July 19*	61.2±	297.1±	0.206	24.8	82.0	$2.7x10^4$	1:0.59:0.40	232	Some aerosol
				29.0	82.9	$8.0x10^4$	1:0.95:0.71	358	conc. instability

* Pump flow-rate could not be maintained at 1 L/min after 10:30. A value slightly less was measured.

+ Before aerosol injection, the following values for N, DR and WL_T were measured: $0.45x10^3$ cm^{-3}, 1:0.14:0.04 and 31, respectively.

Table 7 - Data pertaining to the calibration of the AB-5 #205 and AEP-47 #114 in the RTTF.

Date	$\overline{WL}_{AB-5}$ mWL	$\overline{WL}_T$ mWL	$\overline{WL}_{AB-5}/\overline{WL}_T$	T °C	RH %	N cm^{-3}	DR	WL_T mWL	Remarks
July 15/85	55.4±	52.0±	1.065	24.5	47.5	$0.55x10^3$	1:0.16:0.15	38	
				28.1	52.6	$2.8x10^3$	1:0.33:0.26	70	
July 16	195.9±	247.5±	0.792	24.8	59.7	$6.1x10^4$	1:0.55:0.33	226	Aerosol injected
				26.6	72.9	$7.0x10^4$	1:0.70:0.47	268	at 9:15+
July 17	209.8±	286.4±	0.733	24.3	77.0	$7.2x10^4$	1:0.57:0.39	254	
				27.5	80.0	$7.6x10^4$	1:0.77:0.64	334	
July 18	141.8±	285.0±	0.498	24.7	80.2	$7.5x10^4$	1:0.65:0.58	253	
				25.7	82.8	$8.0x10^4$	1:0.90:0.73	333	
July 19*	105.6±	297.1±	0.356	24.8	82.0	$2.7x10^4$	1:0.59:0.40	232	Some aerosol
				29.0	82.9	$8.0x10^4$	1:0.95:0.71	358	conc. instability

* Pump flow-rate could not be maintained at 1 L/min after 10:30. A value slightly less was measured.

+ Before aerosol injection, the following values for N, DR and WL_T were measured: $0.45x10^3$ cm^{-3}, 1:0.14:0.04 and 31, respectively.

Table 8 - Data pertaining to the calibration of the AB-5 #208 and AEP-47 #119 system in the RTTF.

Date	$\overline{WL}_{AB-5}$ mWL	$\overline{WL}_T$ mWL	$\overline{WL}_{AB-5}/\overline{WL}_T$	T °C	RH %	N cm^{-3}	DR	WL_T mWL	Remarks
July 22/85	189.0±5.6	246.8±7.6	0.766	22.1	82.0	$4.6x10^4$	1:0.55:0.26	252	Aerosol injected
				23.8	83.4	$7.0x10^4$	1:0.78:0.51	275	at 8:45+
July 23	171.5±13.9	264.4±16.0	0.649	21.4	83.9	$6.0x10^4$	1:0.56:0.43	260	
				24.7	84.3	$7.0x10^4$	1:0.82:0.60	318	
July 24	135.6±14.0	243.4±14.4	0.557	22.6	83.9	$6.8x10^4$	1:0.59:0.33	234	
				25.9	84.2	$7.0x10^4$	1:0.85:0.71	288	
July 25	92.3±7.3	244.1±11.8	0.378	24.9	85.3	$6.8x10^4$	1:0.57:0.42	238	
				25.4	85.7	$7.2x10^4$	1:0.79:0.65	280	
July 26	71.9±12.1	255.4±10.0	0.282	23.6	83.0	$6.5x10^4$	1:0.63:0.51	256	
				27.1	85.3	$7.0x10^4$	1:0.86:0.80	292	

+ Before aerosol injection, the following values for N, DR and WL_T were measured: $2.1x10^3$ cm^{-3}, 1:0.11:0.04 and 23, respectively.

Table 9 - Data pertaining to the calibration of the AB-5 #207 and AEP-47 #111 system in the RTTF.

Date	$\overline{WL}_{AB-5}$ mWL	$\overline{WL}_T$ mWL	$\overline{WL}_{AB-5}/\overline{WL}_T$	T °C	RH %	N cm^{-3}	DR	WL_T mWL	Remarks
July 22/85	168.8±5.3	246.8±7.6	0.684	22.1	83.0	$4.6x10^4$	1:0.55:0.26	252	Aerosol injected
				23.8	83.4	$7.0x10^4$	1:0.78:0.51	275	at 8:45+
July 23	156.8±18.3	264.4±16.0	0.593	21.4	83.9	$6.0x10^4$	1:0.56:0.43	260	
				24.7	84.3	$7.0x10^4$	1:0.82:0.60	318	
July 24	127.6±11.9	243.4±14.4	0.524	22.6	83.9	$6.8x10^4$	1:0.59:0.33	234	
				25.9	84.2	$7.0x10^4$	1:0.85:0.71	288	
July 25	81.6±8.8	244.1±11.8	0.334	24.9	85.3	$6.8x10^4$	1:0.57:0.42	238	
				25.4	85.7	$7.2x10^4$	1:0.79:0.65	280	
July 26	62.2±12.3	255.4±10.0	0.244	23.6	83.0	$6.5x10^4$	1:0.63:0.51	256	
				27.1	85.3	$7.0x10^4$	1:0.86:0.80	292	

+ Before aerosol injection, the following values for N, DR and WL_T were measured: $2.1x10^3$ cm^{-3}, 1:0.11:0.04 and 23, respectively.

Table 10 - Data pertaining to the calibration of the AB-5 #205 and AEP-47 #114 system in the RTTF.

Date	$\overline{WL}_{AB-5}$ mWL	$\overline{WL}_T$ mWL	$\overline{WL}_{AB-5}/\overline{WL}_T$	T °C	RH %	N cm^{-3}	DR	WL_T mWL	Remarks
July 24/85	229.4±2.3	243.4±14.4	0.942	22.6	83.9	$6.8x10^4$	1:0.59:0.33	234	
				25.9	84.2	$7.0x10^4$	1:0.85:0.71	288	
July 25+	263.8±13.6	244.1±11.8	1.081	24.9	85.3	$6.8x10^4$	1:0.57:0.42	238	
				25.4	85.7	$7.2x10^4$	1:0.79:0.65	280	
July 26	266.6±15.5	255.4±10.0	1.044	23.6	83.0	$6.5x10^4$	1:0.63:0.51	256	
				27.1	85.3	$7.0x10^4$	1:0.86:0.80	292	

+ Alpha-particle count increased from 13:00 on for no apparent reason.

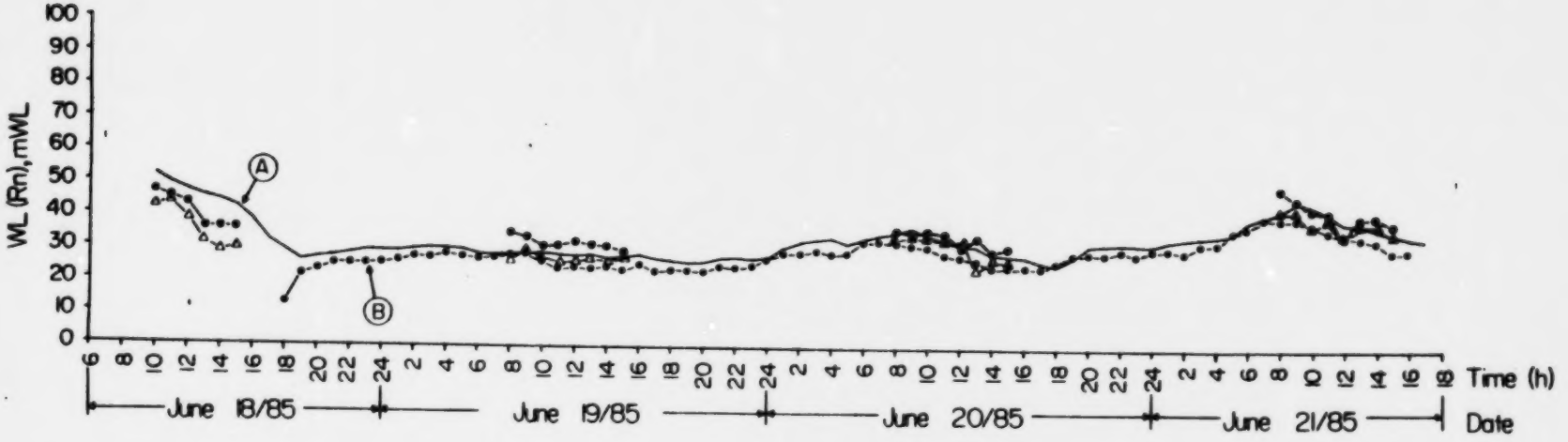

Fig. 1 - Working Level versus time for the systems AB-5 (#208)/AEP-47 (#119), curve A, and AB-5 (#207)/AEP-47 (#111), curve B. Encircled dots and triangles represent grab-sampling data by the Thomas method and Kusnetz method, respectively.

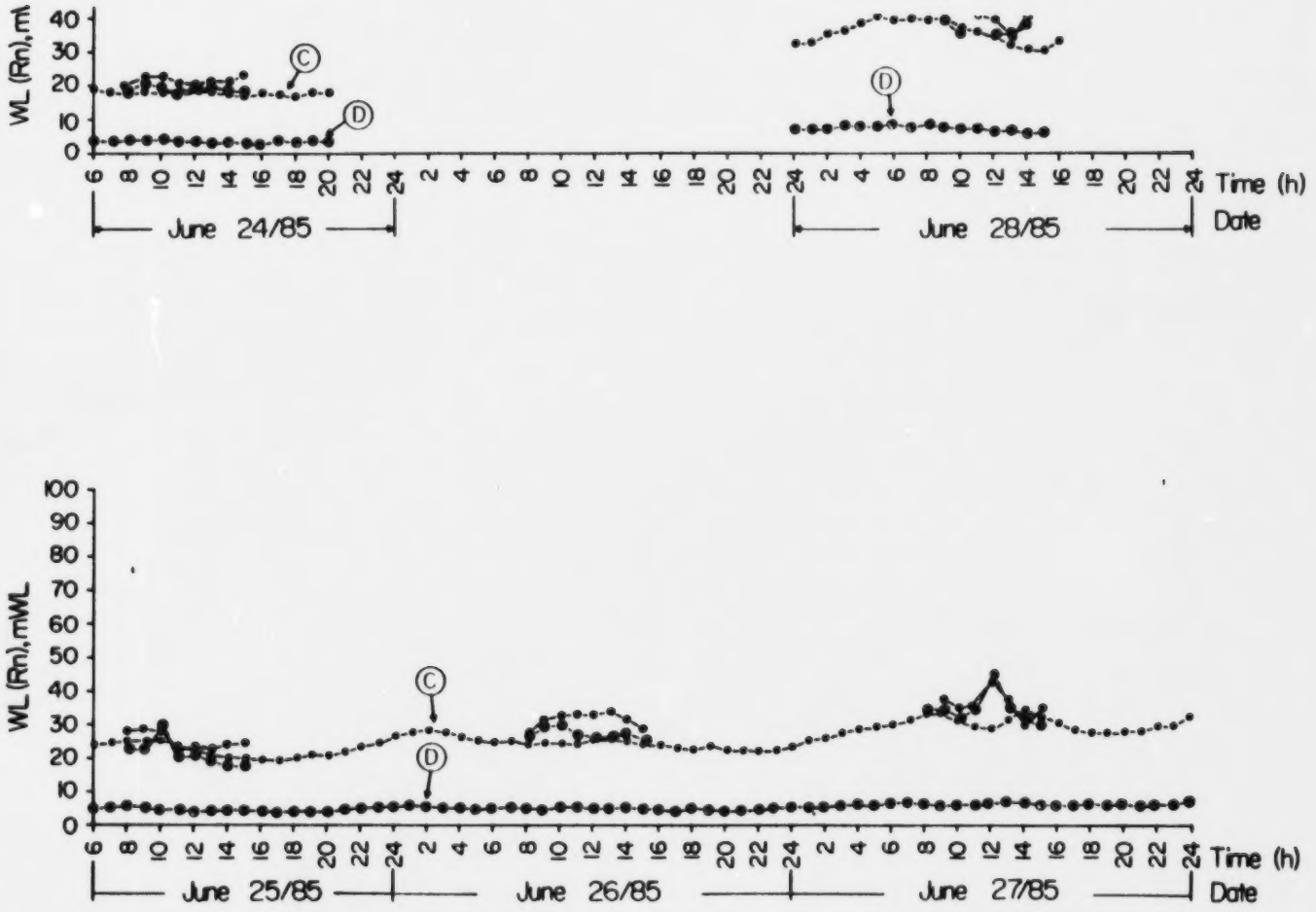

Fig. 2 - Working Level versus time for the systems AB-5 (#209)/AEP-47 (#108), curve C, and AB-5 (#202)/AEP-25 (#106), curve D. Encircled dots and solid dots represent grab-sampling data by the Thomas method and the Kusnetz method, respectively.

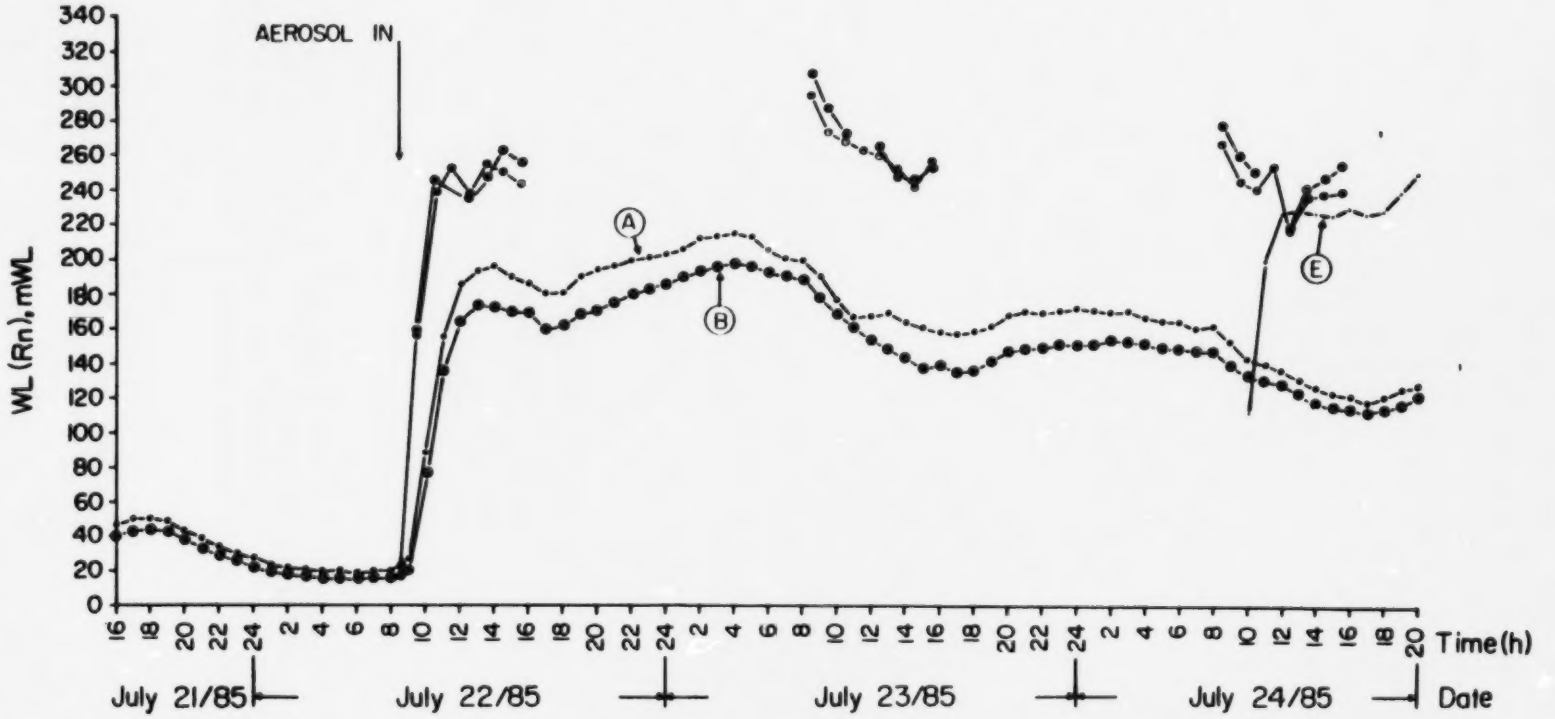

Fig. 5 - Working Level versus time for the systems AB-5 (#208)/AEP-47 (#119), curve A, AB-5 (#207)/AEP-47 (#111), curve B, and AB-5 (#205)/AEP-47 (#114), curve E. Encircled dots and solid dots represent grab-sampling data by the Thomas method and the Kusnetz method, respectively.

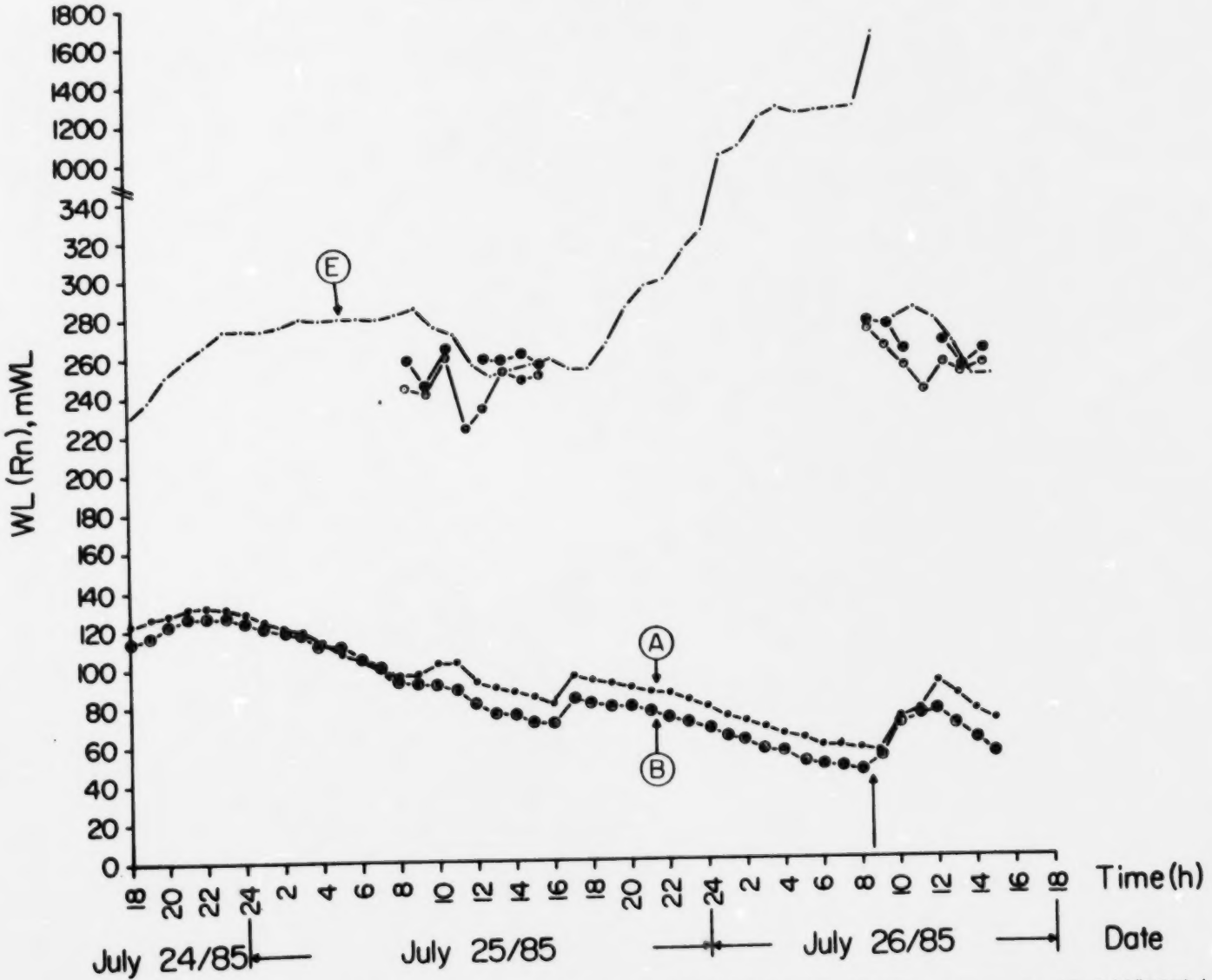

Fig. 6 - Working Level versus time for the systems AB-5 (#208)/AEP-47 (#119), curve A, AB-5'(#207)/AEP-47 (#111), curve B, and AB-5 (#205)/AEP-47(#114), curve E. Encircled dots and solid dots represent grab-sampling data by the Thomas method and the Kusnetz method, respectively.